Low-Swirl DLN Injector for < 5 ppm NO_x Gas Turbines

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Work supported by DOE-DER Low Emissions Turbines
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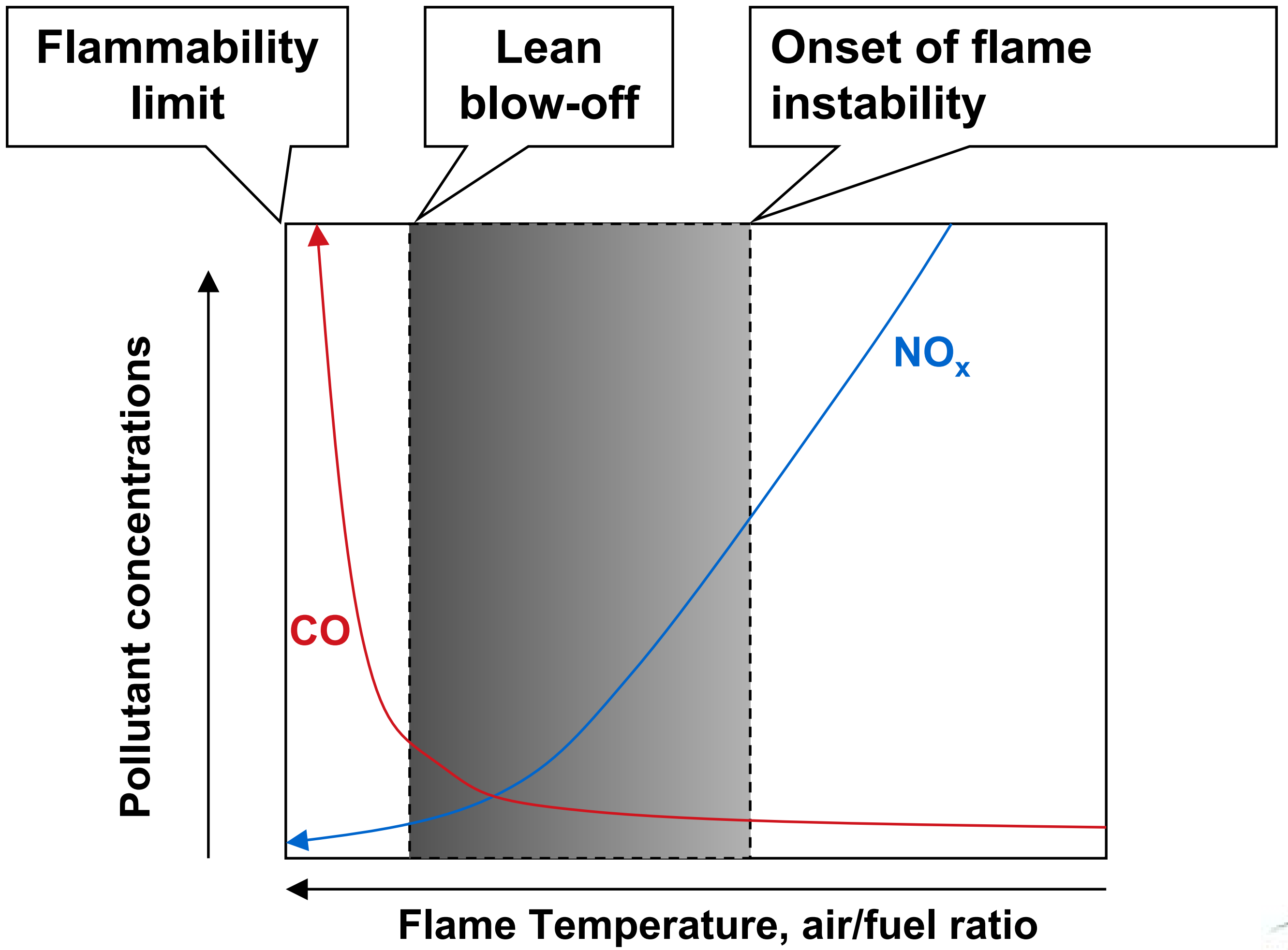
Current DLN Gas Turbine Engines Use High-Swirl Injectors (HSI)

- Centerbody promotes formation of recirculation to entrain and ignite fresh mixture
- Flame attachment at centerbody rim

Lean Blow-off and Flame Instability Are Barriers to Reaching < 5 ppm NO_x



Combustion and Control Methods to Overcome Combustion Dynamics

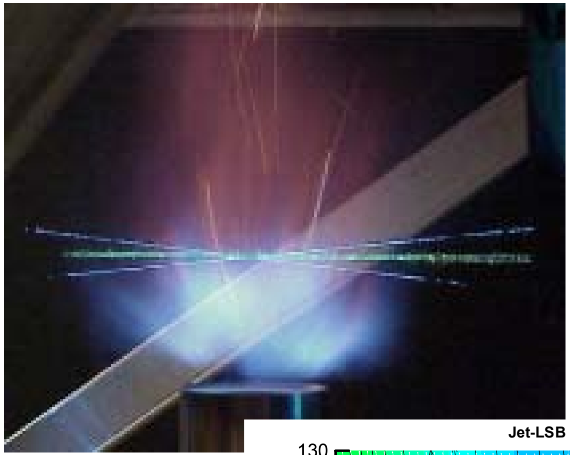
- Combustion methods
  - Catalytic combustors
  - Surfaced stabilized combustion
  - H_2 addition
- Control methods
  - Active or passive
  - Quick response sensors and actuators
- Both solutions have practical and engineering issues involving compatibility, operation, durability, maintenance and cost

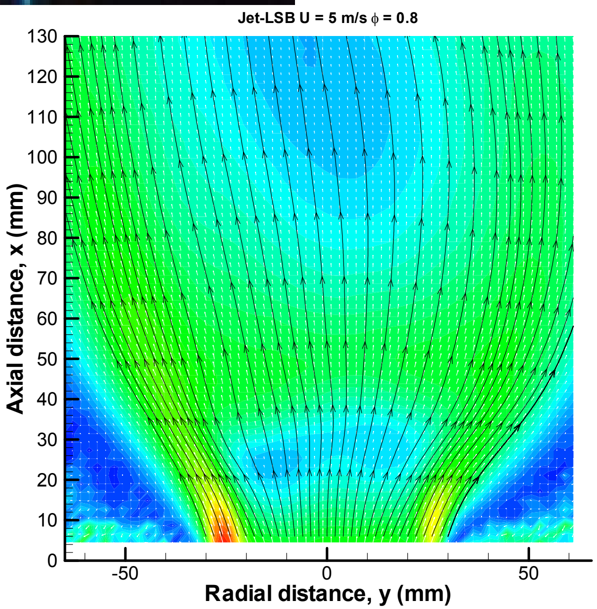
Objective - Improve HSI Performance by Converting to Operate in Low-swirl Mode

- Low-swirl flame stabilization mechanism
  - New concept discovered in 1991 at LBNL from DOE-BES basic research on premixed turbulent combustion
    - **Defies recirculation entrainment theory**
  - Scientific Significance
    - Lacking scientific background for low-swirl flows
    - Challenging modeling and simulation problem
    - Excellent laboratory research tool
  - Technological Interest
    - Ultra-lean flames with low NO_x and CO emissions
    - Simple design, **2 US patents**
    - **Commercialized by Maxon Corp. 2003 for industrial process heat**

Flame Stabilization Mechanism Characterized by Laser Diagnostics

- Flow divergence provides a much more stable mechanism for lean flames than high swirl flows or flame holders
- Flame brush propagates at turbulent flame speed that increases linearly with turbulence intensity
  - flashback conditions predictable
- Swirl intensity controls flame lift off position





Low Swirl Generates a Lifted Flame

This burner is made of PVC and plastic to showcase the uniqueness of LSB

- Lifted flame does not transfer heat to burner throat
- Patented swirler has a center channel instead of a centerbody
- Can be made from low cost materials

Solid Scientific Foundation Led to Equation for Scaling to Different Sizes

$$S = \frac{2}{3}\tan\alpha \frac{1 - R^3}{1 - R^2 + [m^2(1/R^2 - 1)^2]R^2}$$

- Expression uses easily measurable parameters
  - **Ratio of center channel radius to burner radius, $R = R_c/R_b$**
  - **Straight or curved vane with angles, α**
  - **Ratio of mass flow rates through center channel and swirl annulus, *m***
    - **Determine *m* for different screens through pressure drop measurements**

Maxon Commercialized LSB & Identified Significant Economic and Technical Advantages

- Design scales by governing equations
  - A radical departure from experimentation approach
- Size compatible to existing equipment
- Can be fabricated with no initial re-tooling or new patterns required - fewer parts from common materials
- Use existing control for conventional high NO_x burners
- Flame is not in contact with burner tip
  - No thermal stresses to burner that cause metal fatigue
- Lower operational cost, and greater ease of operation, thanks to simpler combustion process

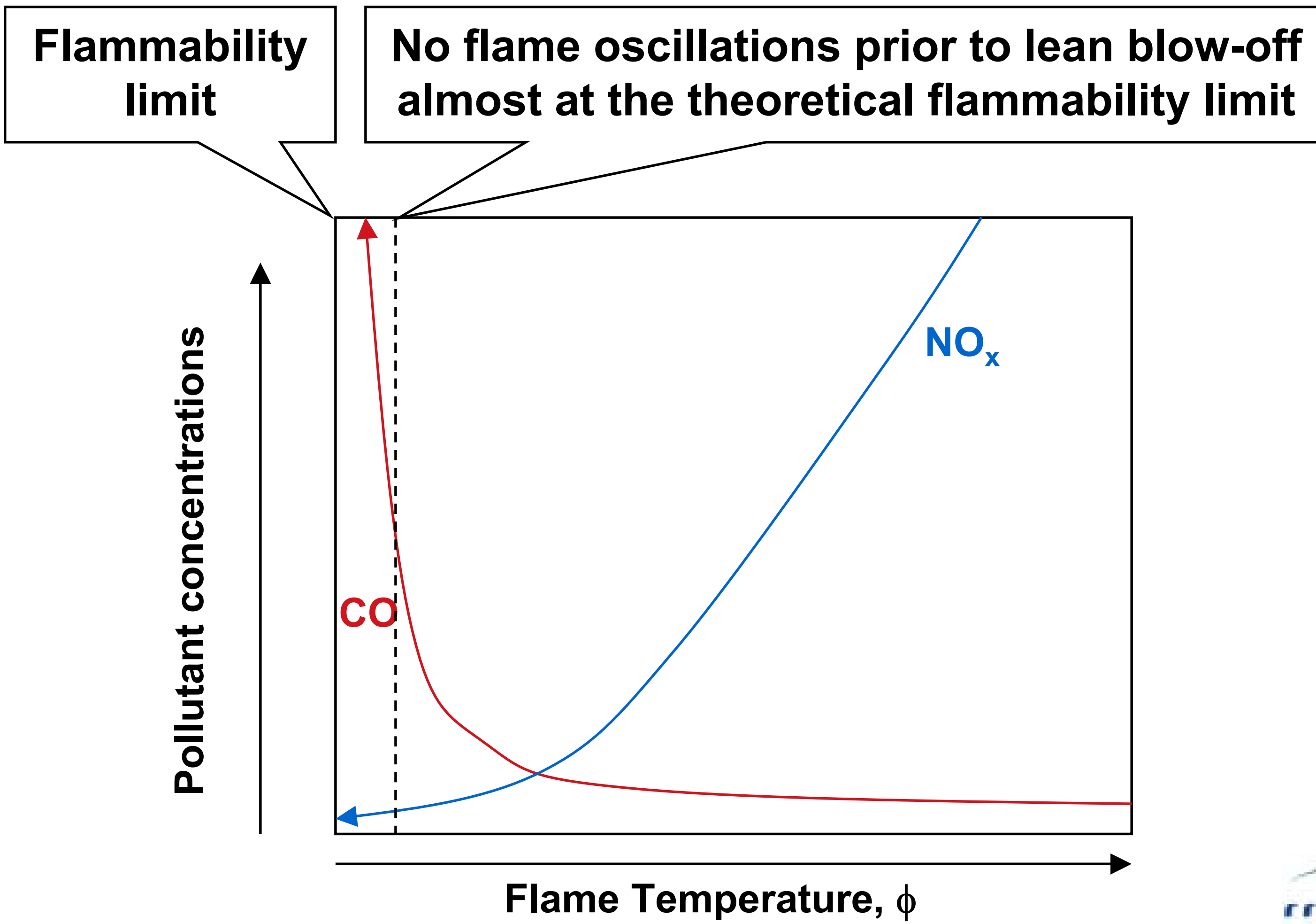
Current Status of LSB Development

- Partnership with more than seven companies
- Burner prototypes from 8 kW (2.5 cm i.d.) to 7 MW (30 cm i.d.) all with ultra-low NO_x capability (< 9 ppm NO_x @ 3% O_2)
- Demonstrated 60:1 turndown
- Demonstrated multi-fuel capability (pure H_2 and other H_2/HC fuel blends)
- Supported by DOE-Office of Industrial Technologies
- Prior supports from Calif. Inst. Of Energy Efficiency and SoCalGas

Adaptation to Gas Turbines

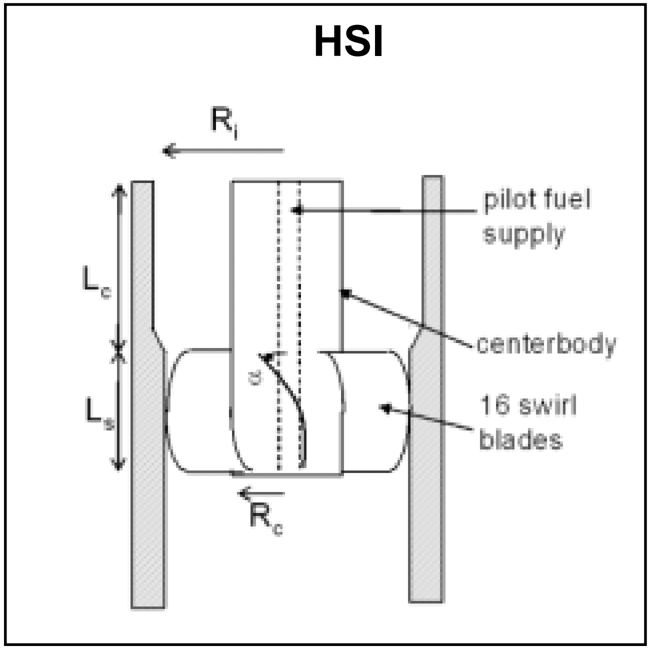
Strives to capture the same benefits and advantages for mid-size Engines

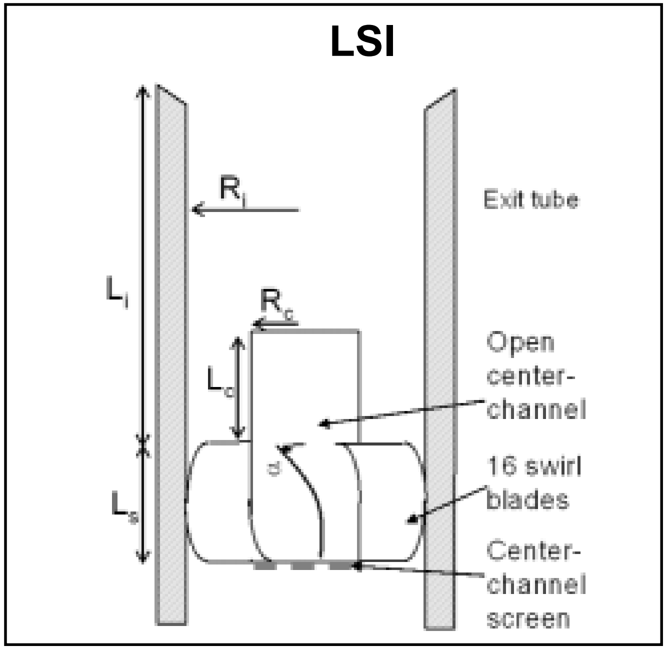
Low-swirl Combustion Exploits Aerodynamics to Overcome the Low-Emissions Barriers



Transferring Low-Swirl Combustion to Gas Turbines

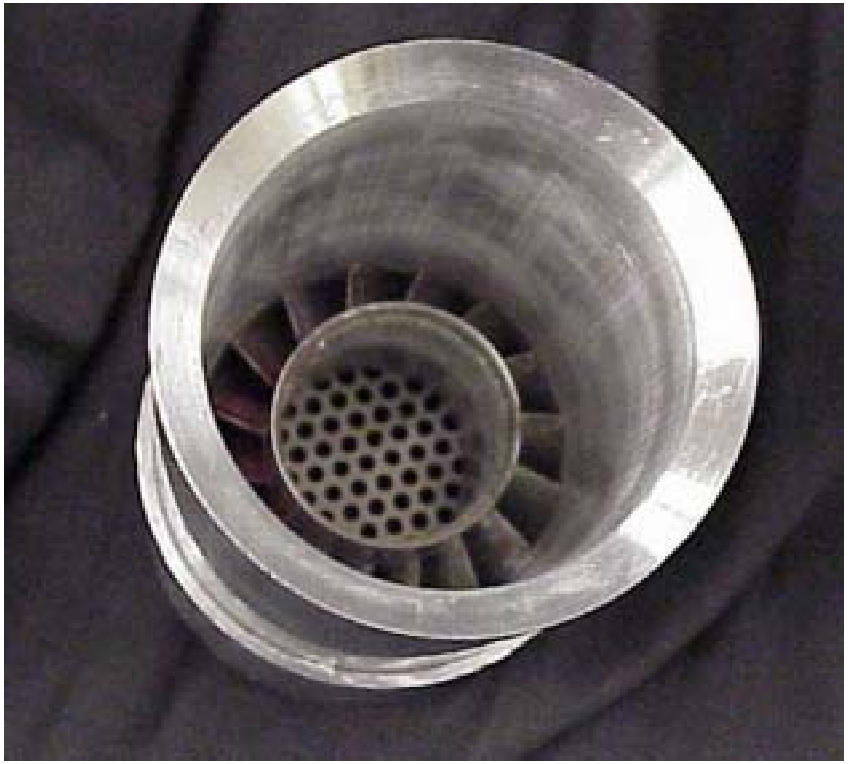
- Reconfigure SoLoNOx injector to low-swirl operation
  - Replace centerbody with perforated S.S. screen
  - Apply guidelines for LSB $0.4 < S < 0.5$, $l_i < 1.5$ D



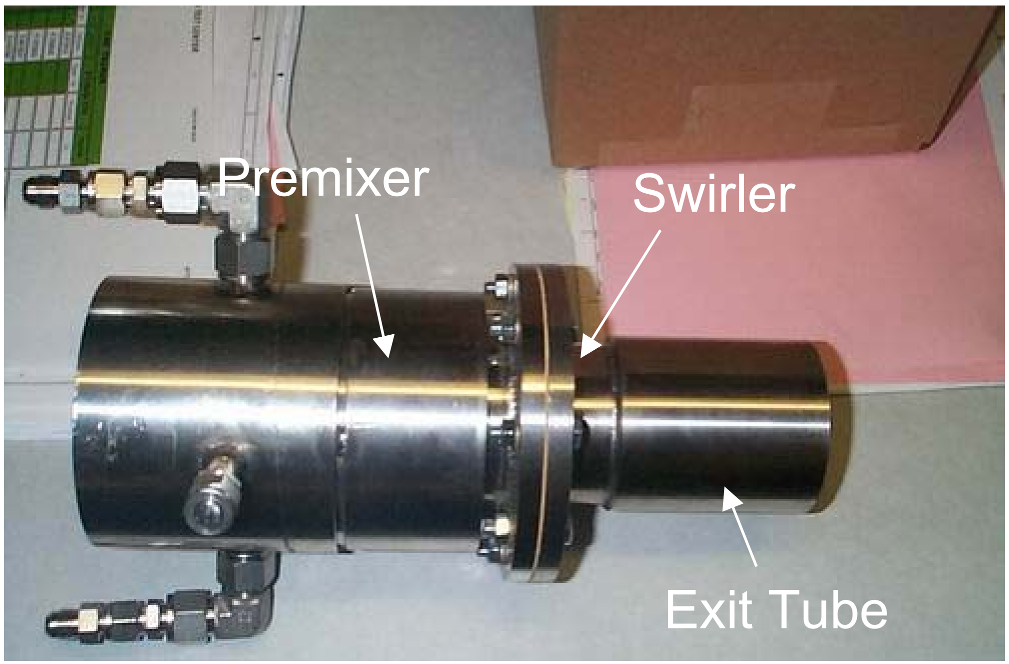


Configured LSI in the Laboratory at Atmospheric Pressure and Low Velocities

- Using different screens to optimize flame lift off height in 6-8 m/s flows
  - Swirl numbers HSI : S = 0.5, HSI: S > 0.7
- Small difference in swirl makes a huge difference in operating principle



LSI for High Temperature High Pressure Rig-tests



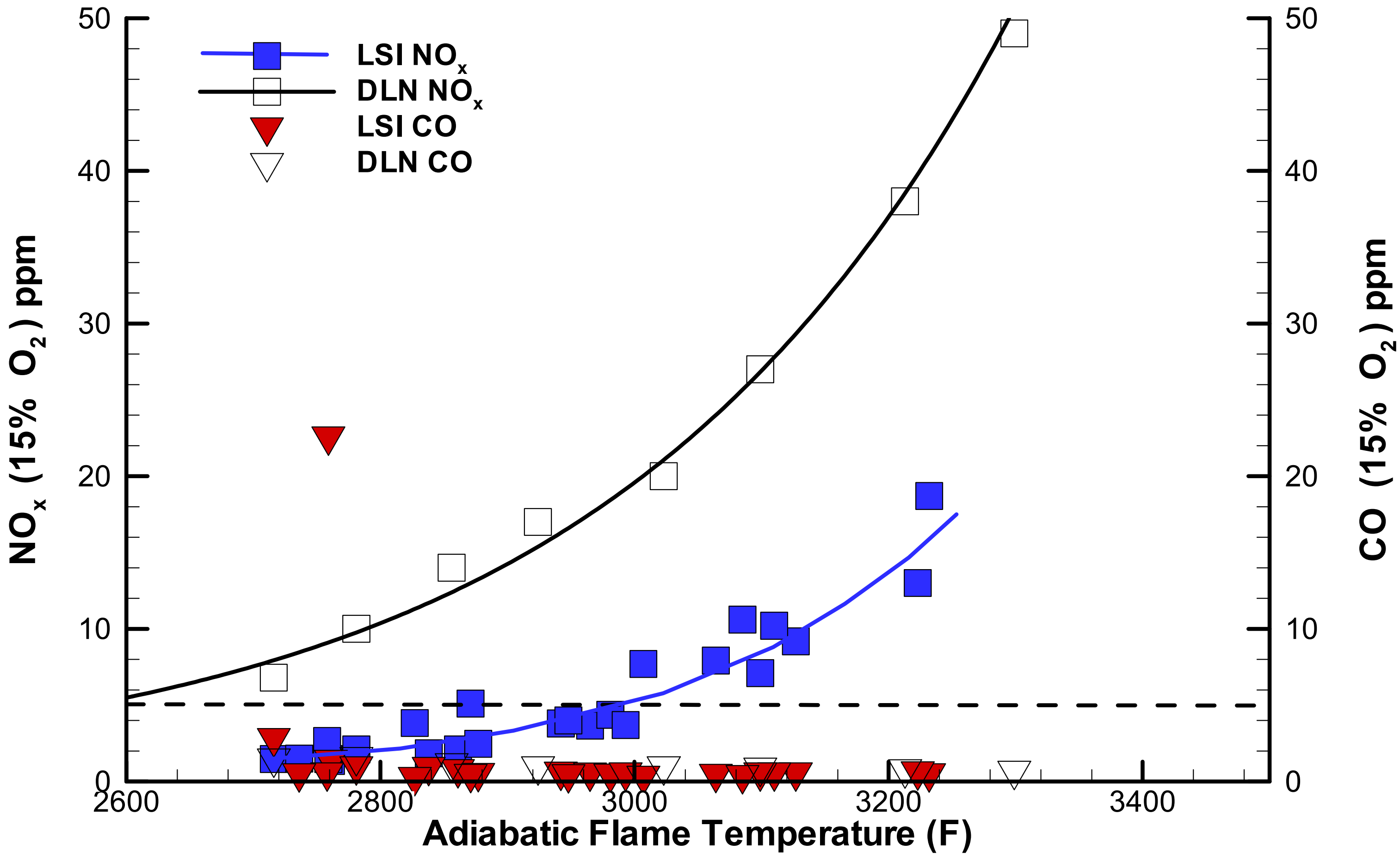
- LSI mounted to premixer with +/- 5% and +/- 10% homogeneity
- Tested in Solar's high pressure rig with an 8" film-cooled louver liner

LSI Rig-Test Conditions

T_o(F)	P_o (atm)	U (ft/s)	Air (lb/sec)	ϕ	Note
440	5	100	1	0.3 – 0.66	
440	10	100	1.8	0.64 – 0.75	
650	10	120	1.8	0.55 – 0.65	
700	10	170	2.6	0.52- 0.7	Taurus 60 full load
800	15	150	3.0	0.54-0.66	Taurus 70 full load

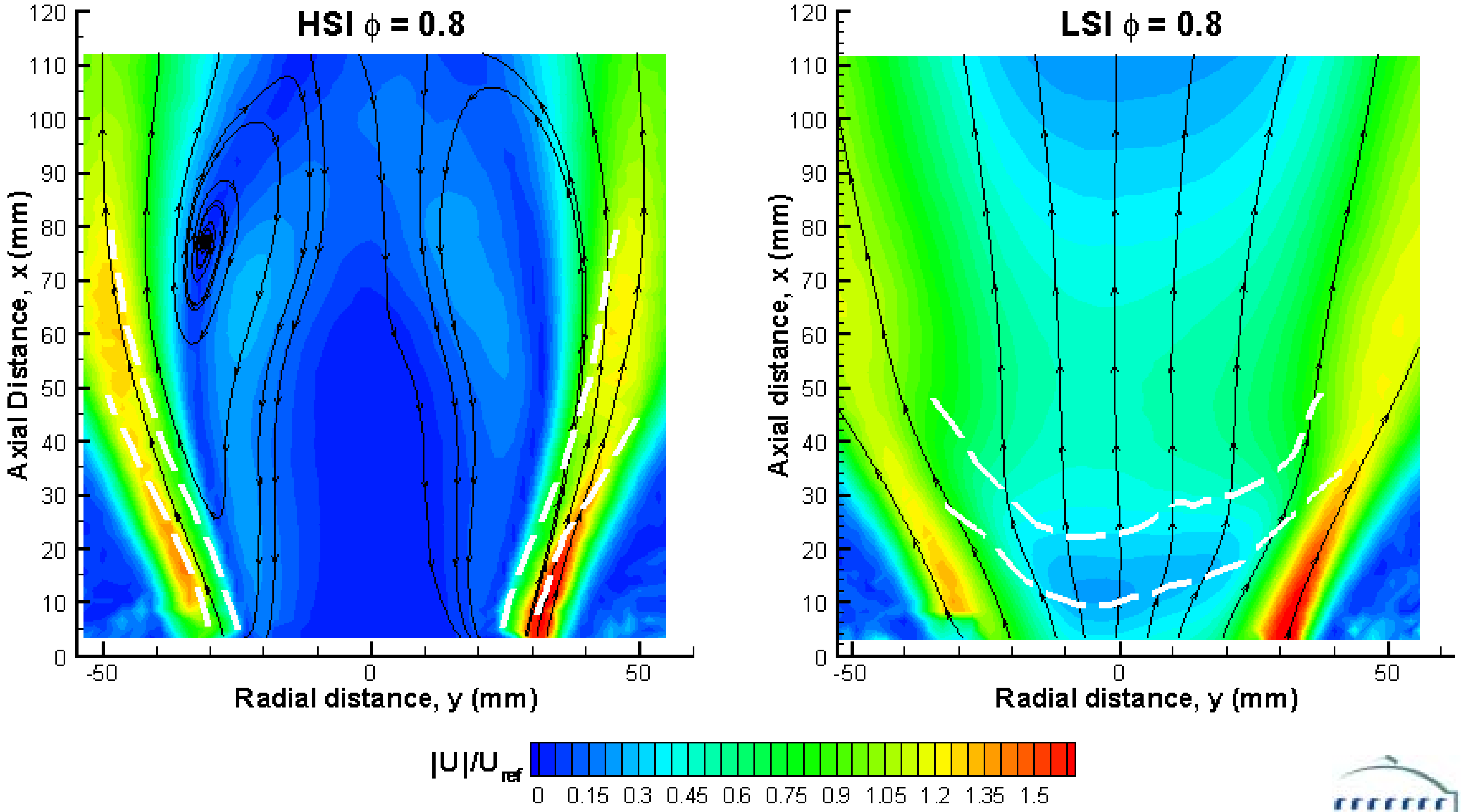
LSI Achieved < 5 ppm NO_x at Full and Partial Load Conditions

- Over 60% NO_x reduction without affecting CO
- Minimum $NO_x \approx 1$ ppm



Absence of Recirculation in LSI May Be Key to Explain NO_x Reduction

- Residence time of hot products greatly reduced



Other Attributes of LSI

- No flame shift or flashback
- Flame robust to withstand large swing in inlet conditions
- LSI has yet to encounter oscillations towards lean blow-off
- Emissions not sensitive to degree of mixedness or pilot

Conclusions on Rig-Test of Low-Swirl Injector Prototype

- Low-swirl combustion method verified under elevated T and P conditions of gas turbines
- Fully compatible with existing mid-size engines
  - LSI prototypes converted from DLN hardware
  - very low add-on cost expected for implementation
- Lowest emissions (< 2 ppm NO_x) matching those of catalytic combustors
  - No compromise on duty cycle time, and a much less elaborate and lower cost alternative
  - NO_x < 5 ppm conditions far from LBO & oscillations
- Shows good promise to maintain low emissions under partial load
  - does not required staging to maintain low emissions under partial load

LSI Development Plan for Mid-Size Engines

- **Current project**
- Address operational issues – piloting, up-load and off-load protocol
  - Emissions, lean blow-off, flame stability, flame spread, and light-off
- Refinement of prototype injector design through single LSI rig-tests and laboratory studies (Target completion 12/04)
- **Future Plan**
- Construct a set of LSIs leading to engine tests and development of scaling guideline
- Select target engine and finalize preproduction design
- Prepare a set of LSI and conduct rig tests
- Develop engine test program and objectives

Planned RD&D Activities on Low-Swirl Combustion

- LSB
  - Process heat – develop enhancement methods with Maxon: staging, internal FGR and preheat
  - Boilers & petroleum refining – continue testing with potential development and commercialization partners
- LSI
  - Mid-size turbines – planned engine test in Winter 2004
  - Micro & utility turbines – seeking research & development partnerships and opportunities
- Enabling technologies
  - Partial reforming – seeking demonstration partners
  - Alternate fuels – demonstrated firing with H_2, HC/H_2, biomass & low-Btu fuels. Seeking R&D opportunities
  - Prevaporized premixed liquid fuels – initiated research at Nat'l Aerospace Lab. of Japan and discussion with U of Wash.
  - Combined heat & power generation – LSB+LSI: seeking R&D opportunities